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Bounds on the Masses and Couplings of Leptoquarks from Leptonic Partial Widths of the Z

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ABSTRACT

The vertex corrections to the leptonic partial widths of the Z induced by leptoquarks that couple leptons to the top quark are considered. We obtain stringent bounds on the parameter space of the masses and Yukawa couplings of these leptoquarks, using the latest information on the $Z \to l^+l^-$ decay widths measured at LEP. Leptoquarks coupling with electroweak strength to top quarks are constrained to be heavier than several hundred GeV, at 95% C.L. As a consequence, such leptoquarks cannot make a significant contribution to lepton asymmetries, τ polarisation asymmetries or A_{LR}.

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In the Standard Model, leptons and quarks are introduced as independent degrees of freedom. However, the requirement of anomaly cancellation relates the hypercharge assignments of the quark and lepton sectors. It is possible that this is a manifestation of a more fundamental symmetry relating leptons and quarks. Indeed, in several extensions of the Standard Model, such as Grand Unified models [1], technicolour models [2], and superstring-inspired E_6 scenaria [3], there exist new boson fields that couple leptons to quarks. Called leptoquarks, they are $\mathrm{SU}(3)_c$ triplets and carry both baryon and lepton numbers. *A priori*, leptoquarks could carry spin 1 or spin 0. It is difficult to incorporate vector leptoquarks in a consistent low-energy theory, so we focus here on scalar leptoquarks that are electroweak doublets and couple to leptons and quarks *via* generalised Yukawa interactions.

If leptoquarks also coupled to quark pairs, their exchanges would violate lepton number (L) and baryon number (B). However, in that case, proton stability constrains leptoquark masses to be comparable to the Grand Unification scale [4]. Therefore, the leptoquarks of phenomenological interest cannot couple to quark pairs and do not violate B and L. Bounds from flavour-changing neutral currents (FCNC) severely constrain flavour mixing in leptoquarks, so we assume [4, 5] that they couple to only a single generation of leptons and a single generation of quarks. Moreover, bounds from helicity-suppressed processes such as $\pi \to e\nu$ decay restrict leptoquark couplings λ_Φ so severely [6] that we assume they are chiral, i.e. each type of leptoquark couples either to left-handed or to right-handed quarks only. These are called left-type and right-type leptoquarks, respectively.

Leptoquarks that do not couple to diquarks and respect these requirements of diagonality and chirality are constrained by searches at e^+e^-, ep, pp and $\bar{p}p$ colliders [7]. The LEP Collaborations exclude any leptoquark weighing less than 45 GeV [8]. The D0 collaboration excludes leptoquarks with first-generation couplings that weigh less than 133 GeV [9], and the CDF collaboration excludes leptoquarks weighing less than 113 GeV [10]. HERA experiments exclude leptoquarks that couple to electrons with electromagnetic strength: $\lambda_\Phi^2 = 4\pi\alpha$, and weigh less than 145 GeV [11]. Besides these direct limits, there are indirect bounds on leptoquarks coming from experiments on parity violation in atomic physics [12, 13] and from searches for flavour-violating Z-decays into leptons [14]. There are also strong FCNC bounds on left-type leptoquarks, due to the fact that CKM mixing renders impossible the diagonality of their couplings, which are reviewed in Refs. [13, 15].

In this letter, we will consider only scalar leptoquarks that transform as doublets under electroweak $SU(2)$, and couple the top quark t to any one of the three lepton generations. This is the variety of leptoquark that is least constrained by the above direct and indirect limits. We also assume that its Yukawa couplings are real. In the case of a left-type leptoquark, electroweak gauge invariance decrees an identical

coupling to the bottom quark b. We show that the LEP measurements of the $Z \to l^+l^-$ partial widths, Γ_{ll}, exclude such leptoquarks if they weigh less than several hundred GeV and couple with the electroweak strength: $\lambda_\Phi^2 = g_2^2 = 4\pi\alpha/\sin^2\theta_W$ [1]. The upper limits on λ_Φ^2 from Γ_{ll} are, in fact, so tight that the leptoquark contributions to the leptonic asymmetries, τ-polarization asymmetry and the forward-backward asymmetry A_{LR} must be much smaller than the experimental errors for any value of the leptoquark mass.

The part of the Lagrangian that describes the couplings of the leptoquarks to the Z and to the quarks and leptons is given by

$$\mathcal{L} = \frac{\lambda_\Phi \tilde{c}_\Phi}{s_W c_W}(k_1 - k_2)_\mu \Phi^\dagger \Phi Z^\mu + \lambda_\Phi \bar{l}[g_L^t P_L + g_R^t P_R] t\Phi, \tag{1}$$

where $\tilde{c}_\Phi = t_{3\Phi} - Q_\Phi s_W^2$ and λ_Φ is the Yukawa coupling ($s_W \equiv \sin\theta_W, c_W \equiv \cos\theta_W$). We now consider the process $Z \to l^+l^-$, and compute the one-loop corrections induced by the $t - l - \Phi$ coupling. Since the leptoquark is assumed to couple chirally, we will have to take either ($g_L^t = 1, g_R^t = 0$) for a left-type leptoquark or ($g_L^t = 0, g_R^t = 1$) for a right-type leptoquark. For the left-type leptoquark, we have to consider both (t,Φ)- and (b,Φ)-induced vertex corrections (with $g_L^t = g_L^b$) [2] while for the right-type leptoquark, the vertex correction is only due to (t,Φ). For the sake of simplicity we also assume that there is only one leptoquark multiplet at a time and there is no mass splitting within it. This assumption is justified if $m_\Phi \gg m_W$, and supported by the agreement between the CDF direct measurement of m_t and the estimate based on radiative corrections, which assumes that no other electroweak doublet has isodoublet splitting large enough to contribute significantly to the isospin-violating parameter $\Delta\rho$, also known as T or ϵ_1. We note in passing that such a degenerate electroweak-doublet leptoquark does not contribute to S (ϵ_3) or $U(\epsilon_2)$.

The relevant triangle and self-energy diagrams for the $Z \to l^+l^-$ vertices are shown in Fig. 1. Following Passarino and Veltman [16], we compute the amplitudes for the diagrams in Fig. 1 in terms of the B- and C- functions corresponding to the two- and three-point integrals, respectively. In terms of the generic internal masses m_1 and m_2, the B-functions are defined as

$$\begin{aligned} B_0 &\equiv \frac{1}{\pi^2}\int d^4k \frac{1}{(k^2+m_1^2)\{(k-p)^2+m_2^2\}}, \\ B_\mu &\equiv \frac{1}{\pi^2}\int d^4k \frac{k_\mu}{(k^2+m_1^2)\{(k-p)^2+m_2^2\}} \equiv -p_\mu B_1, \end{aligned} \tag{2}$$

[1] This strength appears to us as a reasonable standard of comparison, given the large mass of the t-quark and its large Yukawa coupling: $\lambda_t^2 \approx g_2^2$ in the Standard Model.

[2] In a basis in which the up-quark mass matrix is diagonal, there are also (d,Φ) and (s,Φ)-contributions. However, these are suppressed by CKM-mixing. We have checked that their effects are small and we have neglected them.

and the C-functions as

$$C_0, C_\mu, C_{\mu\nu} \equiv \frac{1}{\pi^2}\int d^4k \frac{1, k_\mu, k_{\mu\nu}}{(k^2+m_1^2)\{(k-p)^2+m_2^2\}\{(k-p')^2+m_2^2\}}, \tag{3}$$

with

$$\begin{aligned} C_\mu &\equiv -p_\mu C_{11} + q_\mu C_{12}, \qquad\qquad (q = p - p') \\ C_{\mu\nu} &\equiv p_\mu p_\nu C_{21} + q_\mu q_\nu C_{22} - (p_\mu q_\nu + q_\mu p_\nu)C_{23} + g_{\mu\nu}C_{24}. \end{aligned} \tag{4}$$

The amplitudes for the set of diagrams shown in Fig. 1 can be written as

$$M_\mu^{(i)} = \frac{N_c}{16\pi^2}\frac{e\lambda_\Phi^2}{s_W c_W}\bar{l}(p')\gamma_\mu A_i l(p), \tag{5}$$

where $i = 1, 2, 3$. Here $i = 1, 2$ denote the contributions from the first and the second triangle diagrams, and the contribution of the two self-energy diagrams are jointly denoted by $i = 3$. For the sake of simplicity, we present the expressions for the A_i for the right-type leptoquark (which involve only the top quark inside the loop):

$$\begin{aligned} A_1 &= \left[a_L^t m_t^2 C_0 - a_R^t\{M_Z^2(C_{22} - C_{23}) + 2C_{24}\}\right] P_L, \\ A_2 &= -2\tilde{c}_\Phi \tilde{C}_{24} P_L, \\ A_3 &= a_L^l B_1 P_L. \end{aligned} \tag{6}$$

In the above expressions we have taken $N_c = 3$, and a_L^f and a_R^f are the tree-level Z couplings to the left- and right-handed fermion-flavour f, given by

$$M_\mu^{tree} = \frac{e}{s_W c_W}\bar{f}(p')\gamma_\mu(a_L^f P_L + a_R^f P_R)f(p). \tag{7}$$

where

$$\begin{aligned} a_L^f &= t_3^f - Q_f s_W^2, \\ a_R^f &= -Q_f s_W^2. \end{aligned} \tag{8}$$

For a left-type leptoquark, the appropriate chirality modifications in eq.(6) can be worked out trivially and we do not write them explicitly.

We point out that the contributions from the individual diagrams are divergent, namely C_{24} in A_1, $\tilde{C}_{24}$ in A_2 and B_1 in A_3. But the divergence cancels when these amplitudes are added, and we are left with a finite correction to the partial width $Z \to l^+l^-$:

$$\delta\Gamma_{ll} = \frac{\alpha(M_Z)M_Z}{3\bar{s}_W^2\bar{c}_W^2} a_H^l \delta a_H^l, \tag{9}$$

where

$$\delta a_H^l = \frac{\lambda_\Phi^2}{16\pi^2} N_c \sum_{j=1}^{3} A_j. \tag{10}$$

Note that we have introduced $\bar{s}_W$ as an effective weak angle measured at the Z scale, and have put the relevant energy scale of the electromagnetic coupling strength, α, in the last two equations. The index H is R for a left-type leptoquark and L for a right-type leptoquark.

Leptoquark loop diagrams analogous to those considered above *also contribute to the photon-electron-electron vertex*. The diagrams for the photon are identical to those in Fig. 1, with the Z lines replaced by photon lines. To illustrate this point, we again take the case of the right-type leptoquark, and substitute in eq. (6) the Z parameters by the photon ones; i.e. we replace a_L^t, a_R^t, a_L^e and $\tilde{c}_\Phi$ by Q_u, Q_u, Q_e and Q_Φ, respectively. It is then straight-forward to check that the sum, δa_H^l (photon), at zero momentum transfer, is not zero, and this has to be adjusted against a counter term contribution of $-\delta a_H^l$ (photon), to ensure exact charge conservation. Then, gauge invariance fixes the corresponding counter term for the Z vertex and, hence, we get the expression of the renormalised amplitude for the Z-vertex as,

$$\delta a_H^l(\text{renormalised}) = \delta a_H^l + \sin^2\theta_W \ \delta a_H^l(\text{photon}). \tag{11}$$

Taking this finite renormalisation into account leads to the following modified version of eq. (9), which we employ for our numerical evaluations

$$\delta\Gamma_{ll} = \frac{\alpha(M_Z)M_Z}{3\bar{s}_W^2\bar{c}_W^2} a_H^l \ \delta a_H^l(\text{renormalised}), \tag{12}$$

where H is R or L, as before, depending whether left-type or right-type leptoquark is under investigation.

For ease of interpretation, we present the analytic form of the leptoquark-induced correction in the asymptotic limit when $m_\Phi \gg M_Z$. As before, we present explicitly only the right-type leptoquark case. The *finite part* of the sum of the A_i in eq. (6), plus the counter term contribution as obtained above, becomes in this limit

$$\sum_{j=1}^{3} A_j + \sin^2\theta_W \sum_{j=1}^{3} A_j(\text{photon}) = \left[(a_L^t - a_R^t)\eta_2(x) + \frac{M_Z^2}{3m_t^2}\left\{a_R^t\eta_1(x) + \tilde{c}_\Phi\eta_3(x)\right\}\right], \tag{13}$$

where $(x = m_t^2/m_\Phi^2)$ and η_1, η_2 and η_3 are given by

$$\eta_1(x) \ = \ \frac{-11x + 18x^2 - 9x^3 + 2x^4}{6(1-x)^4} - \frac{x\ln x}{(1-x)^4} \simeq 0 \ (x \to 0),$$

$$\eta_2(x) = -\frac{x}{1-x} - \frac{x\ln x}{(1-x)^2} \simeq 0 \; (x \to 0), \tag{14}$$
$$\eta_3(x) = \frac{2x - 9x^2 + 18x^3 - 11x^4}{6(1-x)^4} + \frac{x^4 \ln x}{(1-x)^4} \simeq 0 \; (x \to 0),$$

exhibiting decoupling in the limit of large m_Φ.

To obtain limits on the leptoquark mass and the coupling parameters, we now compare these calculations with the experimental values of the leptonic decay widths Γ_{ee}, $\Gamma_{\mu\mu}$, $\Gamma_{\tau\tau}$. We parametrize $\lambda_\Phi^2 = g_2^2 k$, where $k = 1$ corresponds to a leptoquark coupling with the electroweak strength. In Fig. 2 we present $\delta\Gamma_{ee}$ as a function of m_Φ, for $k = 1$. We have evaluated the B- and C-functions required using the code developed in the ref.[17], cross-checking the results by using the standard Feynman parametrisation of the two- and three-point functions and then integrating them numerically. The right- and left-type leptoquark contributions $\delta\Gamma_{ee}$ for couplings of weak $SU(2)$ strength and $m_t = 150, 165$ and 180 GeV are shown in Fig. 2 by solid, dashed and dotted lines, respectively. Both the right- and left-type leptoquarks contribute negatively to $\delta\Gamma_{ee}$ and are consequently constrained by the experimental lower limits. We show in Fig. 2 the 95% lower limits on $\delta\Gamma_{ee}$ obtained from the present experimental value $\Gamma_{ee} = 83.96 \pm 0.22$ MeV [19], by subtracting the Standard Model contribution evaluated for fixed $M_H = 250$ GeV and $\alpha_s(M_Z) = 0.12$ (it is quite insensitive to these choices) and the same values m_t =150, 165 and 180 GeV as previously indicated by the horizontal, solid, dashed and dotted lines, respectively. We see that, even for $k = 1$, a left-type leptoquark up to about 680 GeV is excluded for $m_t = 180$ GeV and a right-type leptoquark weighing up to about 280 GeV. Since the leptoquark-induced contribution $\delta\Gamma_{ee}$ is comparable to the experimental uncertainty in Γ_{ee}, there is significant scope for increased statistics and reduced systematic errors to place significantly stronger bounds on the leptoquark parameter space.

We show in Fig. 3 the constraints on leptoquarks coupling the top quark to e, μ and τ in the two-parameter space (m_Φ, k), obtained by analogous studies of corrections to Γ_{ee}, $\Gamma_{\mu\mu} = 83.90 \pm 0.31$ MeV and $\Gamma_{\tau\tau} = 84.07 \pm 0.36$ MeV. The maximum values of k allowed by the three leptonic partial widths for both right- and left-type leptoquarks are shown for the same three values of m_t considered in Fig. 2. In the case of the $t-\tau$ coupling, the upper bound on k is smaller than that for the $t-e$ coupling, in spite of the fact that Γ_{ee} has a smaller uncertainty than $\Gamma_{\tau\tau}$. This is simply because the Standard Model prediction for $Z \to \tau^+\tau^-$ happens to be closer to the experimental 95% C.L. lower limit.

The leptoquark-induced corrections to the Zl^+l^- couplings also show up in the asymmetries A_{LR}, A^l_{FB} and the τ polarisation parameters A^τ_{POL} and P_τ^{FB}. However, the present experimental errors on these quantities are considerably larger than the maximal leptoquark contributions allowed by the width constraints obtained above.

As an example, we consider A^e, which has the same theoretical expression as A_{LR} and P_τ^{FB}, namely

$$A^e = \frac{r^2-1}{r^2+1}; \qquad r = \frac{a_L^e}{a_R^e}. \tag{15}$$

The leptoquark contribution to this is given by

$$\delta A^e = \frac{4r}{(r^2+1)^2}\delta r, \tag{16}$$

where

$$\delta r = \frac{\delta a_L^e}{a_R^e} - \frac{\delta a_R^e}{(a_R^e)^2}a_L^e. \tag{17}$$

The maximum values of δr and hence of δA^e (folded with the maximum allowed k) allowed for the right- and left-type leptoquarks can be evaluated quite easily using Fig. 3 and Eq. (10), and are displayed in Table 1.

There has been considerable interest in these asymmetry and polarisation measurements recently, stimulated in particular by the apparent discrepancy between the recently published SLD measurement of A_{LR} and the LEP precision measurements. It is difficult to interpret this in terms of new physics beyond the Standard Model, particularly because A_{LR} and P_τ^{FB} have the same theoretical expression (Eq. 15), but differ experimentally from each other (0.1628 ± 0.0077 [18] vs. 0.120 ± 0.012 [19], respectively) and lie on opposite sides of the value expected from other measurements. Nevertheless, we have shown in Table 1 the discrepancy between the SLD measurement of A_{LR} and the Standard Model prediction for m_t=150, 165, and 180 GeV and M_H = 250 GeV. We see that the apparent discrepancy is much larger than the largest possible contribution of a leptoquark allowed by the width analysis summarised in Fig. 3. Therefore, a leptoquark could not explain the A_{LR} measurement, even if the difference with the P_τ^{FB} measurement were to be resolved in its favour [3].

To conclude, we have placed bounds on the masses and Yukawa couplings of $SU(2)$-doublet scalar leptoquarks with (l,t) couplings using the latest measurements of the leptonic partial width of Z at LEP. These leptoquarks evade previous bounds [6, 13] because of their chiral and diagonal couplings to third-generation quarks. Moreover, as statistics on the Z peak accumulate and a better understanding of the detectors leads to smaller systematic errors, our bounds can be improved significantly. Further analysis on precision electroweak constraints on these and other varieties of leptoquark is in progress [20].

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[3]We comment in passing that the types of leptoquarks considered here also contribute to $Z \to \bar{b}b$ and $\bar{\nu}\nu$ decays, but that these are also negligible, in view of the previous bounds from $\Gamma_{ee,\mu\mu,\tau\tau}$.

References

[1] For reviews see P. Langacker, *Phys. Rep.* **72** (1981) 185.

[2] E. Farhi and L. Susskind, *Phys. Rep.* **74** (1981) 277 and references therein.

[3] J.L. Hewett and T.G. Rizzo, *Phys. Rep.* **183** (1989) 193 and references therein.

[4] W. Buchmüller and D. Wyler, *Phys. Lett.* **B177** (1986) 377.

[5] J.C. Pati and A. Salam, *Phys. Rev.* **D10** (1974) 275.

[6] O. Shanker, *Nucl. Phys.* **B204** (1982) 375; **B206** (1982) 253.

[7] W. Buchmüller, R. Rückl and D. Wyler, *Phys. Lett.* **B191** (1987) 442;
J.L. Hewett and T.G. Rizzo, *Phys. Rev.* **D36** (1987) 3367;
A. Dobado, M.J. Herrero and G. Munnoz, *Phys. Lett.* **B191** (1987) 449; **B207** (1988) 97;
H. Dreiner et al., *Mod. Phys. Lett.* **A3** (1988) 443;
J.L. Hewett and S. Pakvasa, *Phys. Rev.* **D37** (1988) 3165;
N.D. Tracas and S.D. Vlassopulos, *Phys. Lett.* **B220** (1989) 285;
A. Djouadi et al., *Z. Phys.* **C46** (1990) 679;
T.G. Rizzo, *Phys. Rev.* **D44** (1991) 186;
J. Blümlein and R. Rückl, *Phys. Lett.* **B304** (1993) 337;
J.E. Cieza Montavlo and O.J.P. Eboli, *Phys. Rev.* **D47** (1993) 837;
J. Blümlein, E. Boos and A. Pukhov, DESY preprint DESY-94-072 (1994).

[8] DELPHI Collaboration, P. Abreu et al., *Phys. Lett.* **B316** (1993) 620;
L3 Collaboration, B. Adeva et al., *Phys. Lett.* **B261** (1991) 169;
OPAL Collaboration, G. Alexander et al., *Phys. Lett.* **B263** (1991) 123.

[9] D0 Collaboration, S. Abachi et al., *Phys. Rev. Lett.* **72** (1994) 965.

[10] CDF Collaboration, F. Abe et al., *Phys. Rev.* **D48** (1993) 3939.

[11] H1 Collaboration, I. Abt et al., *Nucl. Phys.* **B396** (1993) 3;
ZEUS Collaboration, M. Derrick et al., *Phys. Lett.* **B306** (1993) 173.

[12] P. Langacker, *Phys. Lett.* **B256** (1991) 277;
P. Langacker, M. Luo and A.K. Mann, *Rev. Mod. Phys.* **64** (1992) 87.

[13] M. Leurer, *Phys. Rev. Lett.* **71** (1993) 1324; Weizmann Institute Preprint WIS-93/90/Sept-PH.

[14] M.A. Doncheski et al., *Phys. Rev.* **D40** (1989) 2301.

[15] S. Davidson, D. Bailey and B.A. Campbell, *Z. Phys.* **C61** (1994) 613.

[16] G. 't Hooft and M. Veltman, *Nucl. Phys.* **B153** (1979) 365;
G. Passarino and M. Veltman, *ibid.* **B160** (1979) 151.

[17] B. Mukhopadhyaya and A. Raychaudhuri, *Phys. Rev.* **D39** (1989) 280.

[18] The SLD Collaboration, K. Abe et al., preprint SLAC-PUB-6456, March 1994.

[19] The LEP Collaborations ALEPH, DELPHI, L3 and OPAL, and the LEP electroweak working Group, as presented by B. Pietrzyk, in the *Proceedings of the XXIX Rencontres de Moriond* (Méribel, France, March 1994), to appear. We thank A. Gurtu for providing us with the Standard Model reference points for various choices of the top mass using the ZFITTER code.

[20] G. Bhattacharyya, J. Ellis and K. Sridhar, work in progress.

Figure captions

Fig. 1 The one-loop Feynman diagrams contributing to the $Z \rightarrow e^+e^-$ vertex correction due to a leptoquark.

Fig. 2 The leptoquark-induced contribution ($\delta\Gamma_{ee}$) to the electronic partial width of the Z as a function of m_Φ, for $k = 1$. The two sets of curves correspond to the left-type (L) and right-type (R) leptoquarks. The solid, dashed and dotted lines correspond to m_t = 150, 165 and 180 GeV, respectively. The three horizontal lines correspond to the allowed values of $\delta\Gamma_{ee}$ for the same choices of m_t, obtained by computing the differences between the corresponding Standard Model predictions and the 95% C.L. lower limit obtained from the experimental data: $\Gamma_{ee} = 83.96 \pm 0.22$ MeV.

Fig. 3 The maximum value of k obtained by comparing the left-type (L) and the right-type (R) leptoquark-induced contributions and the experimentally-allowed window for new physics in leptonic partial widths shown in Fig. 2. Curves are shown for e, μ and τ final states for our previous choices of m_t = 150, 165 and 180 GeV (solid, dashed and dotted lines, respectively).

Table 1: Maximum allowed contributions from left-type (L) and right-type (R) leptoquarks to A^e for $m_t = 150$, 165 and 180 GeV. The differences between the experimental 95% upper (lower) limits and the Standard Model predictions are also shown.

m_t (GeV)	Maximum leptoquark contributions		Experimental uncertainties	
	$\delta A^e(L)$	$\delta A^e(R)$	δP_τ^{FB} (LEP)	δA_{LR} (SLAC)
150	0.0028	-0.0022	0.0075 (-0.0405)	0.0417 (0.0109)
165	0.0047	-0.0036	0.0037 (-0.0443)	0.0379 (0.0071)
180	0.0066	-0.0051	-0.0004 (-0.0484)	0.0338 (0.0030)